WOODS HOLE OCEANOGRAPHIC INSTITUTION

Applied Ocean Physics and Engineering Department, Senior Scientist

February 27, 2015

Dr. Kyle Becker
Office of Naval Research, Code 322
One Liberty Center
875 North Randolph Street
Arlington, VA 22203-1995

Dear Dr. Becker:

Enclose please find the Final Report for ONR Grant No. N00014-14-1-0541 entitled "Three-Dimensional Ocean Noise Modeling," Principal Investigators Dr. David Barclay and Dr. Ying-Tsong Lin.

Sincerely,

Gretchen McManamin
Administrative Associate

Enclosure

cc: Grant and Contract Services (WHOI)
AOPE Department Office (WHOI)
ONR REG Boston N62879
✓ Defense Technical Information Center
Naval Research Laboratory

Final Report
ONR Grant #N00014-14-1-0541

Three-dimensional ocean noise modeling

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Long-Term Goals

The long-term goal of this research program is to provide accurate predictions of ambient noise spectral, temporal, and spatial properties in complex and dynamic metrologies and ocean environments, including those where three-dimensional propagation effects are significant. The development of theoretical and computational models capable of such predictions will necessarily incorporate the investigation of noise source physics, propagation physics and the oceanographic environment, as they relate to noise field statistics.

Objectives

The initial objective of this project is to validate the use of an efficient computation noise model for accurately predicting the spatial properties of ocean ambient noise fields in arbitrary, realistic and complex three-dimensional bathymetry. This is achieved by using a parabolic equation (PE) propagation model and the reciprocity principle applied to the computed complex pressure field.

Additionally, the development of a theoretical framework for describing the noise field in longitudinally invariant environments (in particular, an infinitely long Gaussian trench) was carried out using the method of normal mode decomposition in three-dimensions.

Approach

Using existing WHOI acoustics group azimuthally decoupled two-dimensional (Nx2D) and cylindrical three-dimensional (3D) PE models, the range dependent contribution of each patch of surface noise to a receiver placed at the location of the source can be calculated by a running a single instance of the model and invoking the principal of reciprocity. This can be defined as the range dependent sensitivity to surface noise for a hydrophone at depth, which gives an effective surface-listening radius, and would traditionally be called the transmission loss.

The total noise is calculated by summing over each range-indexed noise source multiplied by the effective area. To compute a probability density function for the total noise, the noise source pressure level at each range-step can be modeled as normally distributed, by the central limit theorem, since each range-step represents an ensemble average of multiple wave-breaking events captured within the effective area of the individual model grid-point. The combination of the normally distributed source pressure levels over the domain of the model, as a function of a random variable, results in a noise level probability distribution function at the receiver.

Vertical coherence can be calculated by running the computation twice, with the source displaced by a relative vertical distance d between each simulation. The range dependent complex pressures near the surface from the two simulations combine to give the cross spectral density between two sensors with a vertical separation of d. For plane wave noise fields, the coherence result can be scaled for sensors spaced at any separation, provided the frequency is scaled accordingly. In both the Nx2D and cylindrical 3D model cases, the vertical coherence as a function of azimuth can be computed, as well as the omni-directional vertical coherence.

Additionally, a theoretical model for the power spectral density, and vertical and horizontal coherence in longitudinally invariant waveguides has been developed with particular attention paid to the case of Gaussian canyon. The solution to the three-dimensional wave equation in Cartesian co-ordinates can be

written in terms of a modal decomposition, carried out in the vertical and across-canyon horizontal directions.

Work Completed

1. Nx2D and 3D Noise PE modeling

The three-dimensional cylindrical PE model and Nx2D PE model have been used to calculate vertical coherence curves that were benchmarked against known wave-number integral solutions in deep water (Cron and Sherman, 1962) and in a shallow water Pekeris waveguide (Deane et al., 1997). The models were then used to calculate the 3D effects on the noise level probability distributions (Figure 1) and vertical coherence as a function of azimuth in the Hudson Canyon (Figure 2).

Additionally, the PE-reciprocity noise model was used to estimate the size, speed and distance from the receiver of a moving rainstorm in the Philippine sea, from data collected during the NPAL PhilSea '09 cruise (Barclay, 2013). The model was also used to explain the horizontal noise directionality observed in the Tonga Trench (Barclay, 2014), which was found not to be a 3D effect, but rather due to bathymetric shadowing.

2. 3D Normal mode solution in a Gaussian Canyon

A quasi-analytical normal mode solution can be described for the noise field in three-dimensional Cartesian space, where the general idealized model geometry contains a pressure release sea surface, rigid-bottom seabed, iso-velocity water column, and a topography $H(y)$ that is range dependent in the y coordinate, but range independent in the x coordinate, or longitudinally invariant. In most cases, including that of the Gaussian canyon, H(y) will be of a form that does not allow the analytical modal expansion of the sound field, however the method of finite difference can be used to calculate the mode shapes. While the vertical and y-horizontal components of the sound field are written as a two unique indexed sums of normal modes, the x-horizontal component is written as the solution to the one-dimensional wave equation in free space.

The noise field power spectral density and coherence can then be expressed as the integral over the product of these solutions: the modal sums and the free space solution. For certain terms, the orthogonality of the modes simplifies the calculation. In general, examining the cross-modal amplitudes and neglecting a substantial amount of terms whose amplitudes fall below a given threshold can significantly reduce the complexity of the noise field computation.

A complete discussion of this work in the form of a manuscript is in preparation for the Journal of the Acoustical Society of America.

Results

Numerical modeling of ambient noise mean level and vertical coherence shows the 3D propagation effects in the example of the Hudson Canyon. The probability distribution of the received noise level as a function of azimuth shows that horizontal reflection and refraction are significant when computing the directionality and the peak level of the noise. The difference between the Nx2D and cylindrical 3D PE models shown in Figure 1 shows a narrowing of the noise propagating along the canyon axis with an increased mean level, while the noise arriving from directions across the axis of the canyon remains unaltered.

Similarly, the real component of the vertical coherence of the cylindrical 3D PE modeled noise arriving on the axis of the canyon has significantly perturbed zero-crossings when compared to the equivalent Nx2D result.

Theoretical work on a simple 3D vertical and horizontal normal mode decomposition model in longitudinally invariant environments, including a Gaussian canyon, may explain these effects.

Impact & Applications

The potential relevance of this work to the Navy is in the areas of passive sonar and noise forecasting. Accurate calculation of mean noise levels, and vertical and horizontal coherence in regions where 3-D propagation effects are important can increase the effectiveness of passive detection signal processing schemes. Efficient computational models for predicting the spatial properties of the noise

field in arbitrary and realistic ocean domains could be the basis of an operational tool for assessing the effectiveness of passive detection systems under different environmental and oceanographic conditions.

Related Projects

The computational and theoretical components of this project will be continued, while an experimental component will be added in the summer of 2015, in collaboration a joint Marine Environmental Observation Prediction & Response (MEOPAR) and Environmental Studies Research Fund (ESRF) project led by Jasco Applied Sciences, Dr. Chris Taggart (Dalhousie University) and Dr. Hilary Moors-Murphy (Department of Fisheries and Oceans, Government of Canada) that will see the year-long deployment of 21 passive acoustic monitoring moorings supported by gliders and wave-rider measurements over the Scotian Shelf, Grand Banks and Labrador Sea. Additionally, a MEOPAR field project to quantify noise using a vertical array in the Salish Sea (Straight of Georgia) has been proposed and will be used to test the predictive abilities of the PE-reciprocity noise modeling scheme. Recent ambient noise data from the Challenger Deep, Mariana Trench collected in December 2014 in collaboration with Dr. Michael Buckingham (Scripps Institution of Oceanography) is currently being analyzed.

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Meeting Proceedings

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Lin, Ying-Tsong, et al. "Three dimensional underwater acoustic modeling on continental slopes and submarine canyons." *The Journal of the Acoustical Society of America* 136.4 (2014): 2317-2317.

Figures

(a)

(b)
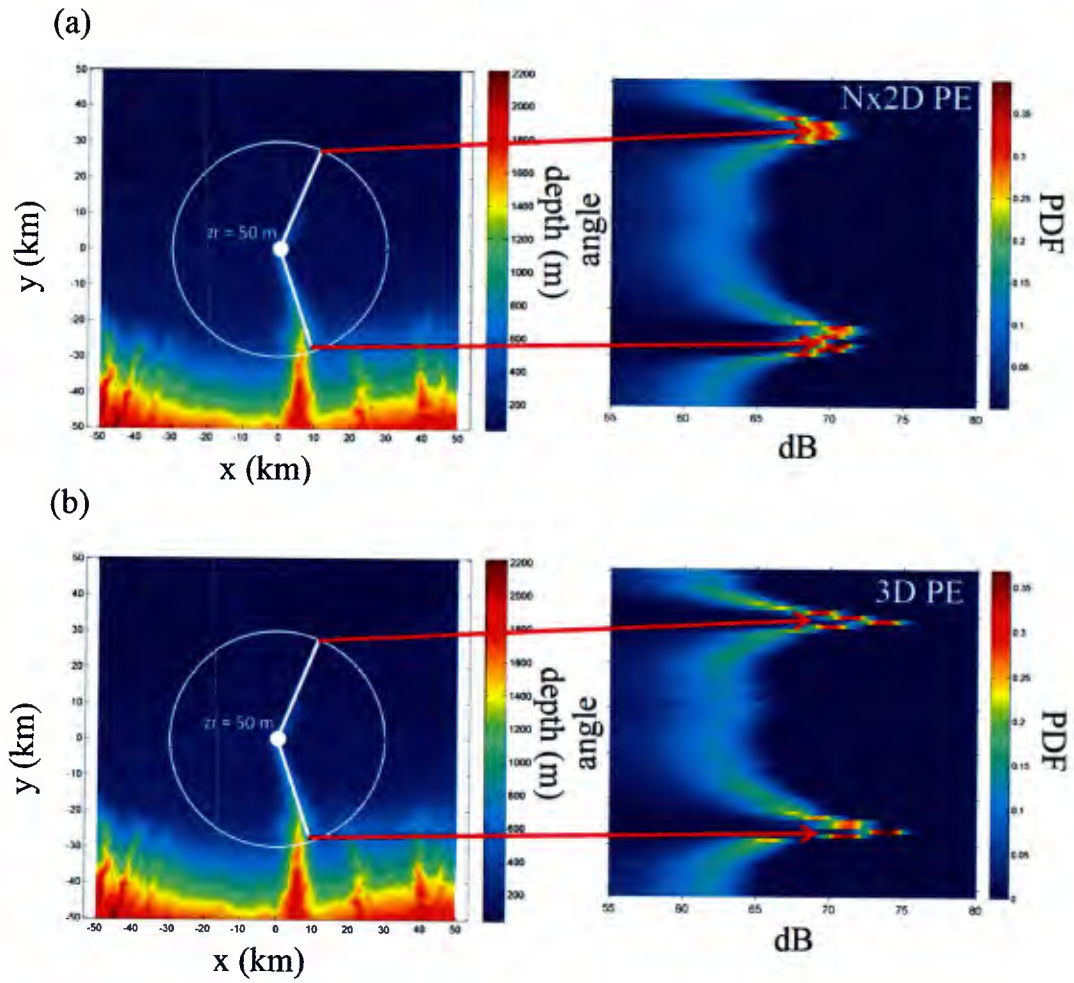
Figure 1. *The noise probability density as a function of azimuth for a receiver placed at 50 m depth in the realistic bathymetry shown (Hudson Canyon), as calculated by (a) an Nx2D PE model and (b) a cylindrical 3D PE model. 3D effects are present in the received noise level for noise arriving along the axis of the canyon.*
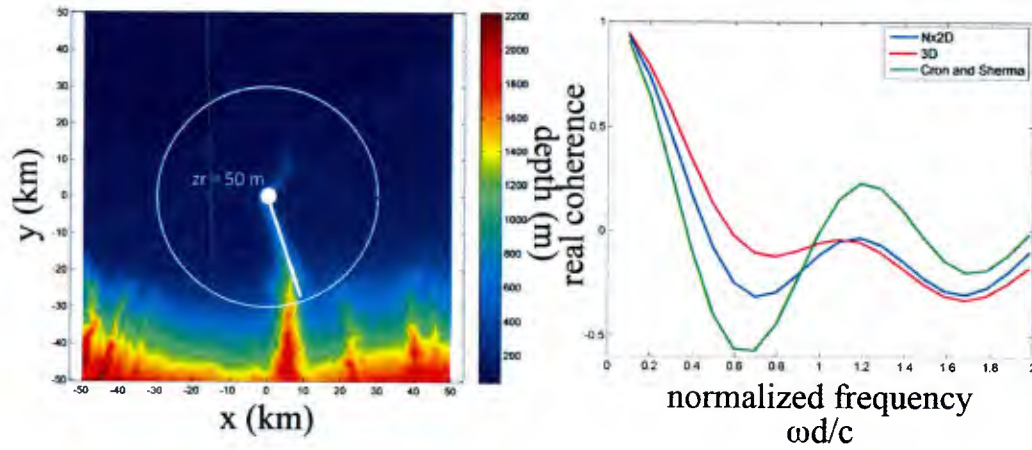
Figure 2. *The real component of the vertical coherence for noise arriving at a receiver at 50 m depth, from the offshore axis of Hudson Canyon, calculated using the (a) Nx2D noise model (blue) and (b) cylindrical 3D noise model (red). For reference, the Cron and Sherman model for noise in an infinitely deep iso-velocity ocean is plotted (green). 3D propagation effects along the canyon axis perturb the frequency of the coherence zero-crossings.*

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Approved for public release; distribution is unlimited

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None

14. ABSTRACT

The objective of this project is to validate the use of an efficient computation noise model for accurately predicting the three-dimensional spatial properties of ocean ambient noise fields in arbitrary, realistic and complex domains. This can be achieved by applying the reciprocity principle of the wave equation to the complex pressure field calculated by a Nx2D or cylindrical three-dimensional parabolic equation (PE) propagation model. The probability distribution function of the noise power spectral density, and the horizontal and vertical coherence can be calculated from the PE model output. Additionally, a theoretical framework for describing the noise field in three-dimensional longitudinally invariant environments (in particular, an infinitely long Gaussian trench) is described using the method of normal mode decomposition.

15. SUBJECT TERMS
Underwater Acoustics, Ambient Noise, 3D propagation, Parabolic Equation, Normal Modes

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